Punctuated Equilibrium and Technological Innovation in the Polymer Industry*

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Recebido em 29/1/2003 Aprovado em 8/9/2003

ABSTRACT

In evolutionary economics, technological change is closely related to the dynamics of the industrial structure and competition, to the internal organization of firms and to the relation of those firms with their clients, other firms, governments and/or research centers and universities. While some authors have focused on the role of incremental changes and cumulativeness, others have examined the role of radical changes. Using the *punctuated equilibrium* model, this paper presents a case study about the evolution of polyolefin technology, in order to discuss the nature of technological change processes, and how they are related to the industry evolution and the behavior of incumbent and new companies.

KEYWORDS | Innovation; Polymer Industry; Punctuated Equilibrium; Technological Change

JEL-CODES | O30, L2, L65

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* Os autores gostariam de agradecer a Loet Leydesdorff, Koen Frenken, Cooper Langford, Luigi Orsenigo, Marcos Dias, Walter Kaminsky e aos pareceristas anônimos pelos comentários sobre este trabalho.

Resumo

Para a economia evolucionária, a mudança tecnológica está diretamente relacionada à dinâmica da estrutura industrial e de competição, à organização interna das empresas e à relação das empresas com seus clientes, outras empresas, governo e/ou centros de pesquisa e universidades. Enquanto alguns autores têm enfatizado o papel das mudanças incrementais, outros autores têm examinado o papel das mudanças radicais. Através do modelo de *equilíbrio pontuado*, este artigo apresenta um estudo de caso sobre a evolução da tecnologia em poliolefinas, de maneira a discutir a natureza dos processos de mudança tecnológica, e como estes processos estão relacionados à evolução industrial e ao comportamento de empresas novas e estabelecidas.

Palavras-chave | Equilíbrio Pontuado; Indústria de Polímeros; Inovação; Mudança Tecnológica

Códigos JEL | O30, L2, L65

1. Introduction

Following Joseph Schumpeter (1911, 1942), innovation and technological change are social processes related to capitalist economic development. These processes, depending on their nature, may involve radical or incremental changes. In such a context, economic development would be associated with the introduction of innovations that may lead to a period of prosperity — stimulating the introduction of other innovations, their diffusion, and absorption by the market — then followed by a period of stability. This equilibrium is unbalanced by the introduction of other innovations giving birth to a new cycle of growth and development.

Neo-schumpeterian authors have analyzed technological change processes using, as analogy, a model from modern biology called *punctuated* *equilibrium* .[1] According to this model, species evolution is characterized by long periods of stability and marked by abrupt changes when new species emerge.[2] In terms of technological change, the long period of stability would be characterized by incremental changes, and punctuation events would be marked by radical changes associated with the emergence of new technologies.

While some authors have focused on the role of incremental changes and cumulativeness, others have examined the role of radical changes and disruptiveness. These different emphases may result in a misleading dichotomy, rendering technological change a radical or an incremental nature. Based on this discussion, this paper analyses the evolution of polymer technology involving the synthesis of olefin monomers (ethylene and propylene) into polyolefins (polyethylene and polypropylene), which will be then used as inputs by plastic processing companies.

This paper is organized as follows. Section one reviews the evolutionary economic literature dealing with the radical *versus* incremental issue. Section two presents the evolution of the polymer industry and technological evolution, focusing upon the polyolefin segment. Section three analyzes this evolution based on the discussion in the first section. The final section offers the conclusions.

2. Technological change and evolutionary theory

There is a consensus among neo-schumpeterian authors concerning the uncertainty, the discontinuous and cumulative nature, and the non-linear character of innovation and technological change processes. Different emphases have been placed on the radical or incremental features of these processes. But adopting one of those views exclusively would limit the analysis of technological change to predetermined dynamics.

According to Utterback & Abernathy (1975, 1978), a discontinuous technological change generally emerges with the introduction of product

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[1] The punctuated equilibrium concept was developed by Gould and Eldredge in the seventies. According to this concept, biological evolution described in fossil records is characterized by long periods of equilibrium punctuated by abrupt changes (Dennett, 1995). At a first glance this may seem a departure from the darwinian evolution, but according to Dennett (1995) this is not the case. Initially Gould and Eldredge observed that darwinian natural selection does not leave any fossil record along the many intermediary steps. But in the eighties Gould observed that the punctuated equilibrium concept rejected the gradualist view of orthodox darwinian evolution. However, later on Gould observed that the concept was in fact a refinement of the darwinian model but not so rigid as orthodox evolutionists.

[2] In biology this process is named speciation defined as the separation of reproductive species either through a a genetic drift or environmental selection.

innovations by new small-size companies or by companies established in branches of industry. In addition, technological change and innovation processes are also related to stages of industry evolution. Initially, the lack of a dominant design facilitates the entry of companies in the market and the competition among technological alternatives, usually product innovations. During the consolidation of a dominant design, the industrial structure undergoes several changes due to companies' strategies towards standardization. After the standard consolidation, the innovative efforts by those companies that remained in the sector are, in general, process innovations, and the industrial structure enters a phase of maturity and stability.

Following this approach, Tushman & Anderson (1986) also addressed the discontinuous character of technological change. According to them, there are two types of technological discontinuities: *competence-enhancing* discontinuities, related with existing competencies; and *competence-destroying* discontinuities, related to an entirely new set of competencies. Competence-enhancing discontinuities occur during periods of incremental changes after the consolidation of a dominant design, and existing companies are more likely to introduce these kinds of changes. Competence-destroying discontinuities are related to periods of major turbulence when there is no dominant design, and are generally introduced by new companies.

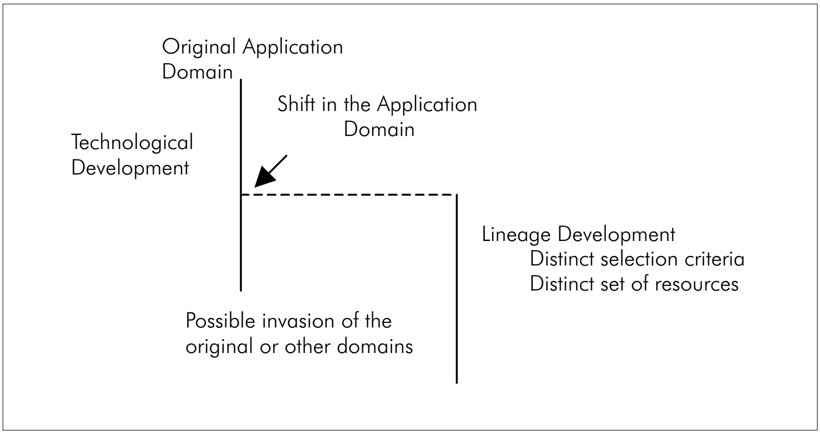
Later on, Anderson & Tushman (1990) argued that after the emergence a competence-destroying discontinuity, a period of instability begins with a fierce competition among technological alternatives. After a selection process with the emergence of a dominant design, a period of stability begins, which is characterized by incremental changes of the dominant standard. This situation is maintained until a new discontinuity emerges.

In contrast to this discontinuous approach, Nelson & Winter (1977, 1982) and Dosi (1982, 1988) have placed more emphasis on the role of incremental change and cumulativeness. According to these authors, technological change processes are related to different selection mechanisms (technological, economic, social and institutional) which affect technological adoption and diffusion. In technological change processes, although there are radical innovations, incremental changes are more frequent than radical changes due to cumulativeness and lock-in effects.

Levinthal (1998) observed that although both views highlight the radical and the incremental features of technological change, there is a difference in emphasis. This emphasis, however, may result in misleading interpretations since generalizations of specific features are rather limited. Therefore, it is not the case of choosing one of those views but of conciliating them.[3]

In Levinthal's view, the nature and the pace of technological change can be examined through the *technological speciation* concept, defined as the application of an existing technology to a certain domain that can lead to a shift in this domain, leading to a lineage development of a new technology. This shift may be due to: 1) changes in problem-solving heuristics; 2) trial and error and/or search and selection within the original knowledge base; 3) fusion of other domains; and 4) other technological, social, or economic aspects. The new emerging technology has distinct selection criteria and a different set of related resources, and it is applied to a new technological domain. This new technology can invade the original technological domain or coexist with it (Figure 1).

Figure 1. Alternative Framework to Technological Change



Source: Adapted from Levinthal (1998)

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[3] For Levinthal (1998) the dichotomization that emerges from the radical *versus* incremental nature of technological change results from the fact that, in economics, evolutionary models have interpreted the *punctuated equilibrium* as a departure from the Darwinian model. But, this interpretation has resulted in a misleading view of technical change, since in biology the *punctuated equilibrium*, as pointed out above, is a refinement of Darwinian evolution.

For Levinthal (1998), a technological lineage development is described by the following processes: 1) technological convergence, when existing technologies (from different domains of application) merge giving rise to a new technology related to an application domain associated to one of the previous domains; and 2) technological fusion, when two or more technologies merge generating a new technology associated with a new domain of application.

The difference between Levinthal and the authors cited above is that for Levinthal (1998) punctuated equilibrium does not mean a radical or a discontinuous approach, but that both radical and incremental changes present cumulativeness as well as disruptiveness. In this sense, his methodological framework offers "a bridge between the notion of the gradual accumulation of scientific knowledge and the phenomenon of dramatic transitions from one technological regime to another in the commercial sphere" (Levinthal, 1998:245).

3. The polymer industry dynamics and technological evolution

The model developed by Levinhtal (1998) was based upon the history of wireless communication technology from Hertz's experiments to cellular phones. In order to understand the technological change, Levinthal (1998) studied the evolution of wireless communication technology to capture the historical events characterizing this evolution regarding both the advances in scientific and the technological knowledge and how these processes were intertwined with the industry's evolution.

Using Levinthal (1998) model, this paper presents an overview of the polymer industry evolution and then focuses upon a given technology used in one of the branches of this industry.

According to Barnett & Clark (1996), the development of new products by polymer companies is directly related to the advances in scientific knowledge in chemistry and chemical engineering (control, design of products, and processes), and has to take into account the technology used by processing companies in order to transform polymers into final products (packages, films etc.). Hence, to understand technological change it is also necessary to understand the effect of this process on the productive chain. It is also necessary to understand the evolution or co-evolution of technologies, organizations, and institutions within the socio-economic environment in which companies, researchers, and other players are embedded.

3.1. Industry evolution

The polymer industry emerged in the middle of the nineteenth century, after the first experiments with modification of natural polymers for commercial applications.[4] However, prior to the 1920s, knowledge of polymers molecular structure was rather limited.

From 1917 to 1920, Herman Staudinger studied organic compounds such as natural rubber, and demonstrated that their molecules comprised chains of monomers. These ideas were not accepted at the time, but they gradually began to receive support after the development of techniques such as ultracentrifuge, polymer viscosimetry, and light scattering (Hage Jr., 1998). Thus, it was only after Staudinger's studies that the term polymer began to designate a wide spectrum of organic chemical products with high molecular weight such as plastics, fibers, and elastomers, among others.[5]

Between the end of the nineteenth century and the beginning of the twentieth century, many polymers were introduced commercially and, in 1909, phenol-formaldehyde, obtained thirty years before, was the first fully synthetic polymer to be commercialized (Utracki, 1995). The most likely explanation for the long period observed between obtaining the molecule and the first commercialization seems to be that other technologies needed to be developed for the product to reach the market. Furthermore, turning these new by-products into goods involved a different transformation process, and thus a new processing industry was needed.

Prior to World War II, scientific and technological efforts were oriented towards a better understanding of polymerization processes to improve the production of those materials. There were, however, many technological limitations that kept the production scale small. According to Utracki (1995:2)

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[4] For example, cellulose nitrate, polyvinylydene chloride and polystyrene were the first man-made polymers introduced that time (Uttracki, 1995).

[5] An organic compound is characterized as a polymer when there is repetition of molecular units (monomers). In synthetic polymers, a chemical reaction must occur to start the polymer synthesis.

"the polymer industry was born in the mid-1800s and emerged from its infancy at the end of the 1930s to begin its two most spectacular decades of expansion", reaching its peak between the 1960s and the 1980s and stabilizing in the 1990s.

From the mid-1950s to the 1960s, expenditures with polymer research and development (R&D) increased substantially. Research efforts continued to be oriented to the development of new molecules, and important advances in polymer science and technology were made. In addition, polymerization and engineering processes attracted considerable attention once it was necessary to scale up production. Demand for polymers had grown strikingly and these products, which had begun to substitute traditional materials in the market, turned into general-purpose materials. Besides, the distance between producers and consumers began to widen, and processing companies started to play a more important role in the product development (Bomtempo, 1994).

From 1960 to 1980, demand was basically for non-differentiated products. In this period, R&D expenditures increased, but in a lower rate compared to the previous period. The role of engineering became more important to the polymer companies' technology strategy since the scale of plants increased, as polymer production had turned into a branch of petroleum industry (Bomtempo, 1994).

The two petroleum crises in 1973 and 1979 also brought changes in the sector, especially in terms of improvements in the use of raw materials and in the process technology. The need to better use the petroleum, a non-renewable resource, led companies to look for diversification of general purpose materials, increasing the number of polymer grades. Such modifications had to be as simple as possible and were to be made by processing companies, which then took a more important role in the product development (Bomtempo, 1994). Another source of change was felt when some companies exited the industry and the producer/consumer relationship became more distant. In addition, during the 1980s, when the sector profitability decreased, there was an overcapacity and the world economy entered into a recession. Due to these factors, polymer companies started to focus on end consumers and, as a result, polymers grades increased substantially, applications became more specific, and R&D efforts continued to be directed to process technology. Besides the renewed interest upon R&D in the 1980s, there were also changes in companies' organization (R&D, marketing, and production became more integrated), and at the end of the 1980s the intensified competition led the polymer industry into a restructuring process through mergers, acquisitions, and joint ventures (Bomtempo, 1994).

In the beginning of the 1990s the polymer industry could be characterized as a mature industry in terms of main companies and available products. But the introduction of a new technology was about to bring a new dynamics into the industry: the introduction of a new type of catalyst in polymerization of olefins.

3.2. Technological evolution of polymer technology: the case of polyolefins

From this point on we focus upon the technological evolution of a particular type of polymers: those resulting from the synthesis of olefin monomers, ethylene, and propylene, called *polyolefins*. These products represent the largest market of the polymer sector, and recent changes, as will be seen next provide an interesting case for the theory of technological change.

The first synthetic polyolefin obtained was the *low density polyethylene* (LDPE) developed by ICI in the 1930s through free radical polymerization process at high pressures.[6] In the following years, the World War II efforts led to the interruption (in Europe) and the slowing down (in the United States) of R&D activities in many sectors. This trend also affected the polymer sector, although some applications for the LDPE were discovered during this time.

After the World War II, research groups from universities and industrial companies restarted their R&D activities. In this period, two new types of polyolefins were obtained: the *high density polyolefin* (HDPE) and the *polypropylene* (PP). The development of these new products involved not only new polymerization techniques but also the development of two new molecules with different properties.

HDPE resulted from almost 20 years of research by Karl Ziegler and co-workers in organometallic chemistry at the Max Plank Institute. Ziegler *et al.*

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[6] The first polymer derived from ethylene, the polymethylene, was obtained by Hans von Pechman in 1898. But, although there was scientific interest upon it, the commercial production of polymethylene was not feasible at that time (Utracki, 1995).

began to research organometallic chemistry in the 1930s,[7] but during the World War II efforts their research was interrupted and only restarted right after the war. In 1953, almost by accident, Ziegler *et al.* obtained a new type of polyolefin, the HDPE, through a process different from the radical free polymerization, used to obtain LDPE. This process involved the use of a heterogeneous catalyst made of zircon acetilacetone and tri-ethylaluminum at low pressures. According to Martin (1995), after Ziegler *et al.* have filled patents for this development, many companies, such as Hoechst and BF Goodrich licensed from Ziegler *et al.* on the new polymerization process and the new polyethylene. But other companies claimed against Ziegler *et al.* patents in order to obtain privileged licenses or to invalidate those patents. Those companies, however, were not successful.

Subsequently, following Ziegler's procedures, Giulio Natta polymerized propylene and obtained the *polypropylene* (PP). According to Martin (1995), Natta filled an Italian patent for PP a little before Ziegler *et al.* filled a German patent. Natta's achievement was a mixture of technical capabilities and opportunistic behavior, since he was aware of Ziegler *et al.* results, but the company in which he was a consultant (Montedison) had an agreement with the Max Planck Institute researchers. In 1963, Ziegler and Natta shared the Nobel Prize for their contribution to the development of heterogeneous catalysts for polyolefins synthesis (Hage Jr., 1998).

From the 1950s to the 1970s polymer companies introduced many improvements in chemical engineering process for synthesizing polyolefins and new generations of ZN catalysts, which also improved the properties of polyolefins. In the 1970s, Union Carbide introduced a new type of polyethylene, the *linear low density polylethyelene* (LLDPE) through a gas phase process.

3.2.1. New catalysts and new polymers

The use of catalysts for the polymerization of olefins began after Ziegler's and Natta's researches. Due to this reason, ZN catalyst became a generic term

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[7] At the end of the 1920s, Staudinger observed that monomers needed to reach energetic activation for the molecular chain to grow. This is reported in the literature as one of the first steps towards the recognition of the role catalysts in polymer synthesis (Hage Jr., 1998).

to describe chemical compounds used in olefin polymerization and copolymerization (Kissin, 1989).

According to Boor (1979), one of the main concerns within polymer research is the range of control of the polymer molecular structure during polymerization. Thus, since the first generation of ZN catalysts in the 1950s, four generations of ZN catalysts were developed allowing a better control of polyolefins molecular structure during polymerization, and a better understanding of polymerization mechanisms. However, even the most recent generations of ZN catalysts are limited in tailoring products once this is still only possible after polymerization.

In the history of polyolefin technology, it could be said that there was a kind of a lock-in effect in terms of catalyst technology for olefin polymerization, since polymer research has focused upon better ZN heterogeneous catalysts. The most likely reasons for this lock-in effect are: 1) increasing returns effects; 2) learning effects; 3) changes in industry dynamics and intensified competition; 4) the cyclical nature of expansion/reduction of industrial capacity; and 5) a growing concern with the future of petroleum feed stocks. These reasons led companies to focus R&D upon incremental innovations, the increasing of polymer grades and improvement of chemical engineering processes.

However, the beginning of the 1980s witnessed the emergence of a new type of catalyst: the metallocene catalyst, which proved to be a homogenous system capable of polymerizing olefins. Although metallocene compounds research has been carried out since the 1950s — when the ZN catalysts were developed, — these compounds have had a lower productivity when compared to the ZN catalysts (Marques *et al.*, 1998). In turn, research on metallocene compounds slowed and focus was placed upon ZN systems. According to Razavi (1995,) the existing paradigm — inherited from the heterogeneous catalysts — of the metallocene catalytic properties was overcame after three decades of slow development, and it involved the discoveries of the new metallocene catalysts.

The first metallocene catalyst capable of polymerizing olefins was obtained by Walter Kaminsky at the University of Hamburg, Germany. In 1968, under the supervision of Professor Hans Jörg Sinn, Walter Kaminsky, a PhD. student, was involved in researching reaction of zirconocenes, a metallocene compound.

At that time, very few scientists were interested in those structures. Under Sinn's supervision, Kaminsky pursued research on the mechanisms of catalysis using metallocenes. For Kaminsky (1998), the obtaining of metallocene catalysts capable of polymerizing olefins was a mixture of chance and systematic research. It occurred after a change in the reaction conditions during a study of the mechanisms of ethylene polymerization. Unexpected results in the reaction moved him to examine the reasons for the outcome carefully. For eight years, Kaminsky and his colleagues were practically the only researchers in metallocene research.

According to Kaminsky (1998), despite this achievement there was not much interest in the discovery once it was possible to produce only polyethylene. It was necessary to polymerize propylene to assure the potential viability of the new catalysts. This became possible only a couple of years later, in 1984, when Kaminsky and his co-workers, and J. Ewen at Exxon worked out different ways to polymerize propylene with metallocenes. Exxon's interests in metallocene catalysis started shortly after a lecture by Kaminksky in 1980. After this lecture, Exxon's researchers began the development of a metallocene catalyst proprietary technology. Afterwards, other polymer companies, especially leading companies, followed Exxon not only in metallocenes research but also in the searching of other alternative compounds that could be characterized as homogeneous catalysts (also called *single site catalysts* or SSC).

The development of the metallocene catalysts and, more recently, other SSC, represents an important scientific and technological advance with great impact upon product development, process technology and upon processing companies.

Such catalysts allow the production of polymers with greater heat and impact resistance, more elasticity and better optical properties, among other qualities in relation to existing polyolefins and grades. This would corroborate a trend observed in the 1990s to increase the value of product technology through the improvement of existing polymers performance.

But the metallocene catalysts also paved the way for new routes in polymer R&D, mainly because the properties of the resulting polymer through SSC can be "programmed". SSC allows for a greater control of polymers molecular structures during polymerization, allowing the tailoring of products for specific applications.[8] These new catalysts have not only allowed obtaining already known molecules that could not be obtained with ZN systems, but also to search for yet unknown molecules. These catalysts may also increase the flexibility of production plants since different products could be obtained in the same plant. Last, these catalysts also improved the understanding of the polymerization mechanisms (Forte *et al.*, 1996; Ribeiro Filho *et al.*, 1997).

Despite of such dramatic impacts, although there has been a substitution effect within polyolefins and in polymerization processes, LDPE, HDPE, PP and LLDPE are still marketed through different technologies, using different ZN catalysts, and for different applications.

4. The dynamics of technological change in perspective

Considering the literature of technological change and the case presented above, two important questions can be raised: 1) how can a technological discontinuity be both disruptive and incremental? 2) how the new SSC may represent a technological rupture without rendering existing competencies obsolete? The answers to these two questions depend on which stage we are focusing, that is, product development, process technology, control of molecular structure, or catalysts evolution.

In terms of the search for new molecules, the SSC have opened the way for obtaining known molecules that were not possible using ZN systems, and have created a "window of opportunity" for the search of new molecular structures. Such disruptive nature of the *single site catalysts* could also be seen when one looks to the degree of control of polymers molecular structure during polymerization. According to Montagna *et al.* (1997), a new technology that represents a greater control of the polymer molecular structure, and new molecule entails a different S-type curve, describing the technology cycle from the initial phase, increasing returns, and maturity stage. Thus, the introduction of metallocene catalysts would represent a fifth S-type curve.

On the other hand, the first SSC, the metallocene catalyst, capable of polymerizing olefin monomers was developed during the research trend observed

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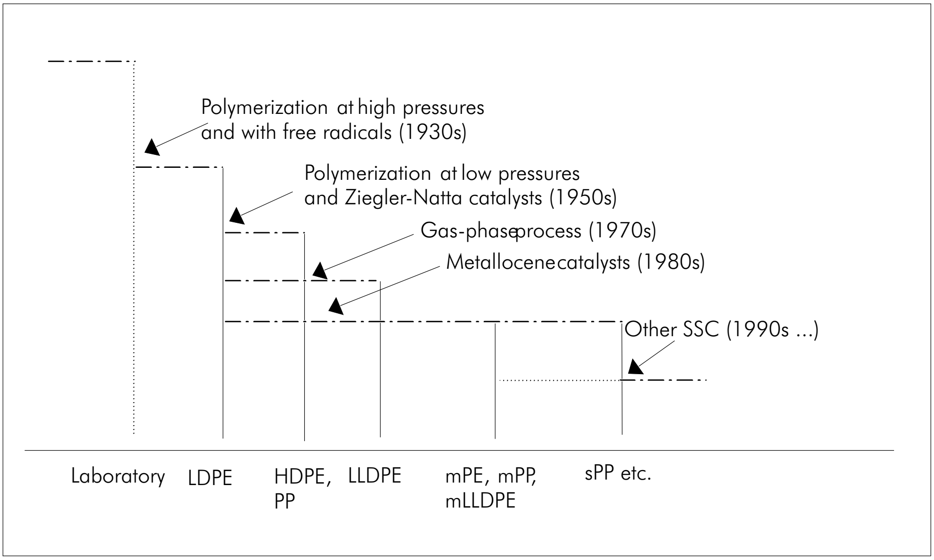
[8] This potential has been enhanced by the advances in simulation techniques and project designing that are making the development of new products and processes more agile.

in the 1980s: the search for improved and high performance grades of traditional polymers, since SSC allow already known polyolefins to be used in different applications. It was only after this that a renewed interest was born both within university research groups and in the industry, paving the way for the search of new types of SSC and also new molecules. Furthermore, the SSC[9] allowed polymer companies to produce different polymers within the same reactor. In turn, companies may become more flexible and reduce the need of large-scale production that has characterized the industry since the 1950s.

Applying Levinthal' (1998) methodology, the evolution of polymer technology related to the polymerization process may be interpreted as a *speciation process* leading to different *lineage developments* characterized by several generations of catalysts and polyolefins. The case presented above could be interpreted as depicted in Figure 2, below:

Figure 2. Evolution in Polyolefin Technology



Source: Adapted from Fialho (1999).

Considering Figure 2, above, the free radical polymerization at high pressures was the first speciation event that led to the first lineage development in the polyolefin technology, resulting in the LDPE. Prior to that, experiments

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[9] Within the same plant, companies may produce a large variety of tailor-made products for specific applications.

with polymers were mainly laboratory experiments that, although not leading to products with industrial application, enhanced the knowledge of such molecules and the means for obtaining them. The second speciation event came about when the ZN catalysts were introduced in polymerization at low pressures, resulting first in HDPE and then in PP. Although HDPE and PP allowed new applications for polyolefins, they also introduced competition within polyolefins. But, for certain applications each of these three products continued to be the most cost effective alternative. The third speciation event was characterized by the development of a new type of polyolefin, the LLPDE, in a gas phase polymerization process. LLDPE competed not only with existing molecules and grades in certain applications but it also allowed new applications. The fourth speciation event was marked by the introduction of metallocene catalysts for olefin polymerization leading to metallocenic polyethylene (mPE and mLLDPE) and polypropylene (mPP). But these catalysts also allowed the obtaining of molecules that were not feasible to obtain with ZN systems as well as new molecular structures. The development of other SSC represents another speciation event that can both be used in existing molecules or open new routes to search for new molecules.

Considering the competencies associated to polyolefin production, the introduction of SSC does not mean necessarily the destruction of competencies in all the segments of the polymer industry. Depending on the stage of transformation, polymer production, or polymer processing, the advances in polymer technology can enhance some of the existing competencies; or can lead to changes in the competence profile. In any case, companies must have qualified human resources with interdisciplinary background and expertise to be able to respond to the new challenges coming from the market.

In terms of product development, the SSC may represent a rupture for processing companies, since with previous ZN catalyst systems the tailoring of products was done after polymerization and mainly by processing companies since the 1980s. Concerning polymer companies the nature of technological change regarding competencies has been different for those incumbents that have developed technological leadership or absorptive capabilities and companies that are technologically dependent. Leading companies have been able not only to cope with change and moving to metallocene and SSC research but also to develop proprietary technology. In this respect, polymer companies are looking for strategic alliances, joint ventures, and cooperation agreements with other companies, universities and research centers, to develop new products and processes. These strategies indicate that polymer companies, especially the world leaders, are trying to establish technological leadership positions since there is no dominant design in SSC polymerization techniques, and there is still room to profit from previous technologies.

But, for technologically dependent companies, the new catalysts may mean, in the future, the rendering of existing capabilities obsolete if there is a full substitution effect between polyolefins obtained with ZN to SSC polyolefins. However, at this moment, this is only a possibility since there are still R&D efforts in ZN systems. Similarly to the previous changes in polyolefin technology, such complete substitution has not been seen. But those technologically dependent companies have moved from high to a low added value markets as new technologies improved mechanical and physical properties of polyolefins for commercial applications.

Another remark must be made regarding the discussion of the role of new and established companies in the introduction of technological discontinuities. Considering the radical nature of the SSC or even the ZN catalysts, according to the discontinuous approach these technological changes would be likely introduced by new companies. However this was not the case. Generally in the case of the development of new knowledge fields, such as ZN and SSC, uncertainty is quite high and academic research groups are more likely to be the loci for the commitment of R&D efforts. Both in the case of ZN and SSC there were observed close ties between universities and industry, either through direct collaboration or through close proximity in seminars and congresses.

Besides, the development of free radical polymerization and ZN catalysts sheds light on another characteristic of industrial and technological evolution that is different from the SSC. In the case of LDPE, HDPE and PP, it involved not only new technology and new molecules but also the establishment of a new industry. In this sense, companies from other related segments, especially chemical companies were the most capable to enter the new field. In the case of SSC, it involved the development of a new technology in a relatively mature segment in terms of technology and available products. But the existing companies were the ones able to recognize and introduce the new products commercially, as well as to benefit from the knowledge spillovers in order to develop proprietary technology or to establish alliances with other companies or academic groups.

Finally, although the first company (Exxon) to enter the new technology (SSC) was not the leader in the prior paradigm (ZN) it was one of the main players in the segment and had established a joint venture at the end of 1990s with Union Carbide (which was a pioneer in the gas phase technology for polyethylene production.) Also, Exxon was followed closely by other companies that were leaders in the prior technology (Fialho *et al.*, 2001).

5. Conclusions

Technological change and innovation are fundamentally evolutionary uncertain and also purposive processes. According to Levinthal (1998), to characterize these processes as radical or incremental processes may obscure the underlying intertwined dynamics of technological, scientific, and industrial evolution. Besides, such a characterization is only possible after the unfolding of different events in different domains.

Based on the case study above, we can also conclude that any change, however incremental, may dramatically alter scientific and technological knowledge base, whereas a typically radical rupture may bring only incremental changes. Besides, it is not always the case that a prior technology becomes completely obsolete when a new technology is launched. There are some technological and economic limitations that may allow or stimulate companies to keep up with "old" technologies that may co-exist with the "new" technologies. In some cases, polymer companies believe it is advantageous to maintain current industrial plants using prior technology, and developing new variants of the existing products, such as new grades, polymer blends, and composites.

As indicated in the history of the wireless communication technology by Levinthal (1998), technological change and innovation have to be seen as historical processes that may have incremental and discontinuous developments that may lead to entirely new generations that are also open to a future speciation process. These processes are also non-linear since there is no unidirectional and prior logic between advances in basic research and the development of new processes and/or products. In addition, technological evolution is closely related to the dynamics of the industrial structure and competition among companies, to the internal organization of companies and to how companies interact with their clients, other companies, governments and/or research centers, and universities.

From our study we could also observe that the gradual or radical nature of the technological change cannot be identified until the trajectory is consolidated. This also depends upon the impact in which part of the value-chain and from which point of view technological change is being analyzed. Furthermore, although there may be incentives to direct research for incremental changes, the events can turn out to be a *radical departure* from the previous technology.

In short, this paper brings up several points of relevance for the study of technological change and innovation. These studies should take into consideration: (1) the dynamics underlying the evolution of intra and inter-industry relationships, in which technological, marketing and organizational strategies are developed; (2) the influence of macroeconomic conditions on the dynamics of industrial and technological evolution; (3) the organizational and institutional formats and the relationships among different companies; (4) the interrelation between these processes (social, technical, and economic) and the advances in scientific and technological knowledge of the disciplines and domains of application; and (5) the pursuit of incremental changes can bring about technological changes with a radical content, which can later lead to incremental changes and vice-versa.

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